



**U.S. ARMY
RDECOM**

TECHNICAL REPORT RDMR-AF-14-01

NINE YEARS OF COOPERATION THE US/GERMAN MEMORANDUM OF UNDERSTANDING (MoU) ON HELICOPTER AEROMECHANICS 2003-2012

Chris L. Blanken

**Aeroflightdynamics Directorate
Aviation and Missile Research, Development,
and Engineering Center**

And

Berend G. van der Wall

**DLR Institute of Flight Systems
Braunschweig, Germany**

December 2013

**Distribution Statement A: Approved for public release;
distribution is unlimited.**



DESTRUCTION NOTICE

FOR CLASSIFIED DOCUMENTS, FOLLOW THE PROCEDURES IN DoD 5200.22-M, INDUSTRIAL SECURITY MANUAL, SECTION II-19 OR DoD 5200.1-R, INFORMATION SECURITY PROGRAM REGULATION, CHAPTER IX. FOR UNCLASSIFIED, LIMITED DOCUMENTS, DESTROY BY ANY METHOD THAT WILL PREVENT DISCLOSURE OF CONTENTS OR RECONSTRUCTION OF THE DOCUMENT.

DISCLAIMER

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

TRADE NAMES

USE OF TRADE NAMES OR MANUFACTURERS IN THIS REPORT DOES NOT CONSTITUTE AN OFFICIAL ENDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL HARDWARE OR SOFTWARE.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 074-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503				
1. AGENCY USE ONLY		2. REPORT DATE December 2013	3. REPORT TYPE AND DATES COVERED Final	
4. TITLE AND SUBTITLE Nine Years of Cooperation The US/German Memorandum of Understanding (MoU) on Helicopter Aeromechanics 2003-2012			5. FUNDING NUMBERS	
6. AUTHOR(S) Chris L. Blanken and Berend G. van der Wall				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Commander, U.S. Army Research, Development, and Engineering Command ATTN: RDMR-ADF-SV Redstone Arsenal, AL 35898-5000			8. PERFORMING ORGANIZATION REPORT NUMBER TR-RDMR-AF-14-01	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (Maximum 200 Words) For 30 years, the United States Department of the Army through the Aeroflightdynamics Directorate (AFDD), AMCOM and the National Aeronautics and Space Administration (NASA), and the German Ministry of Defense (MoD) through the German Aerospace Center (DLR) have mutually benefited from a long-standing Memorandum of Understanding (MoU) for Cooperative Research in the Field of Helicopter Aeromechanics. The mission of this joint venture is to bring together motivated scientists and visionary engineers in order to elucidate corresponding research perspectives. With the ever increasing constraints of national resources this agreement has proven over the last three decades to be a catalyst for effectively reducing the national workloads while widening research capabilities and enhancing research productivity. This MoU is considered a textbook example of a mature, formal exchange agreement.				
14. SUBJECT TERMS Aeroflightdynamics Directorate (AFDD), German Ministry of Defense (MoD), German Aerospace Center (DLR), National Aeronautics and Space Administration (NASA), and Memorandum of Understanding (MoU).			15. NUMBER OF PAGES 53	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102



Nine Years of Cooperation

The US/German Memorandum of Understanding (MoU)

on

Helicopter Aeromechanics

2003 – 2012

Berend G. van der Wall and Chris L. Blanken (editors)

United States Army Aviation and Missile Research, Development, and Engineering
Center Technical Report RDMR-AF-14-01

DLR Institute of Flight Systems, IB 111-2013/33

Preface

For 30 years, the United States Department of the Army through the Aeroflightdynamics Directorate (AFDD), AMCOM and the National Aeronautics and Space Administration (NASA), and the German Ministry of Defense (MoD) through the German Aerospace Center (DLR) have mutually benefited from a long-standing Memorandum of Understanding (MoU) for Cooperative Research in the Field of Helicopter Aeromechanics. The mission of this joint venture is to bring together motivated scientists and visionary engineers in order to elucidate corresponding research perspectives. With the ever increasing constraints of national resources this agreement has proven over the last three decades to be a catalyst for effectively reducing the national workloads while widening research capabilities and enhancing research productivity. This MoU is considered a textbook example of a mature, formal exchange agreement.

Throughout the years, two major areas of research have generated outstanding results in both theory and experiment. These are:

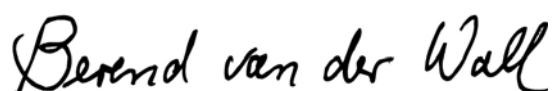
- (1) rotorcraft flight dynamics and control tasks including stability and control analysis, handling qualities research in general and specifically for active controlled rotorcraft, modeling and simulation for rotorcraft systems;
- (2) rotor aerodynamics tasks including rotor aeroacoustics, dynamic stall suppression, rotor wake measurement techniques and individual blade control.

Both areas of research started very early in this MoU and have been active ever since. From this research, the overall products are tools, experimental facilities and mathematical models that are world-class and leading-edge, and which have been published in numerous collaborative and individual publications. One of the major benefits is seen in the complementary facilities available on both sides with respect to a variety of flying helicopter test beds (RASCAL, BO105, EC135) and test facilities (model rotor test rigs, DNW and NFAC wind tunnels, vertical motion and ground based simulators). These have been used by pilots and engineers from both the U.S. and German sides and the data bases were shared, providing exceptional value for the money invested.

The results of this collaboration were incorporated into the ADS-33 handling qualities specification and the detailed research on active rotor control with wind tunnel investigations has brought outstanding improvement of predictive capabilities of rotor aeromechanics and acoustics. The American Helicopter Society has honored these efforts with several of their Awards, exemplarily the AgustaWestland International Fellowship Award given in 1996 for the HART I Test Team and in 2012 for the HART II International Workshop Team, and the Howard Hughes Award for the HART II Test Team in 2004. A common German/US paper about handling qualities of side-stick controlled helicopters was given the “Ian Cheeseman Best Paper Award” at the European Rotorcraft Forum 2012.

As this current period of the MoU ends in September 2012, an amendment for the next period was foreseen. However, rules have changed and a new General MoU has been signed between the U.S. Department of Defense (DOD) and the German MoD in 2009 that will have only Project Agreements (PA) under this umbrella, and such a PA will form the future legal frame of the current MoU. Negotiations are underway and hopefully will be signed in time for a smooth merger into the future of this collaboration.

It shall be mentioned that aside of the pure technical issues covered, a number of personal friendships have developed that persist even after the tasks were closed. New ideas were recently brought up and new tasks were starting to become active. With these engaged personal resources and a widening range of themes, the future of this cooperation can be seen in best light.



Berend G. van der Wall

DLR, German Project Officer



Chris L. Blanken

AFDD, US Project Officer



**Group Photo at the 30th Anniversary of the MoU
Celebrated at Braunschweig (Germany) in 2008**

Table of Contents

1. Introduction	1
2. MoU Historical Overview	3
3. MoU guidelines	5
4. MoU Tasks Overview	7
4.1. Task III: Rotor Aeroacoustics (2003-2009)	7
4.2. Task VII: Dynamic Stall Suppression (2003-2012)	10
4.3. Task VIII: Rotor Wake Measurement Techniques (2003-2012).....	12
4.4. Task IX: Modeling and Simulation for Rotorcraft Systems (2003-2009)	15
4.5. Task X: Handling Qualities for Active Controlled Rotorcraft (2003-2012)	18
4.6. Task XII: Active Individual Blade Control (2009-2012)	26
4.7. Task XIII: Obstacle Field Navigation for Unmanned Rotorcraft (2010-2012)	28
5. Future.....	31
6. Bibliography	33

1. Introduction

A Memorandum of Understanding (MoU) for cooperative research in helicopter aeromechanics between the U.S. Department of Defense (DoD) and the German Ministry of Defense (MoD) has brought together scientist and engineers from both countries to work jointly on applied research problems of helicopters. The work is performed in the U.S. by the U.S. Army Aeroflightdynamics Directorate (AMRDEC) and in Germany by the German Aerospace Center (DLR).

This MoU started in 1979 with semi-annual meetings. There have been several extensions to the original agreement, covering nine-year-periods each, the last one signed in 2003 for the period from 2003 to 2012. This report summarizes the activities performed in the last period of this agreement.

2. MoU Historical Overview

The MoU was initiated by Dr. Irving Statler (Director of the U.S. Army's Aeromechanics Laboratory) and Dr. Peter Hamel (Director of DLR's Institute of Flight Mechanics, which is today's Institute of Flight Systems). The first MoU was signed in the U.S. on October 2, 1978 and in Germany on February 8, 1979, for a period from 1979 to 1982. During that time the first MoU Project Officers were Dr. Irving Statler for the United States and Dr. Peter Hamel for Germany, and the first technical meeting was held in the fall of 1979.

Following a productive initial MoU, the agreement was extended several times with three-year supplemental agreements. In September 1994, a new MoU agreement was signed for a nine-year period from 1994 to 2003, and in September 2003 the extension was renewed for another nine-year period until 2012. This report covers the technical work performed during this last nine-year period.

Due to a new general MoU between the U.S. DoD and the German MoD the future cooperation will be performed under a Project Agreement (PA), and negotiations started already in 2010.

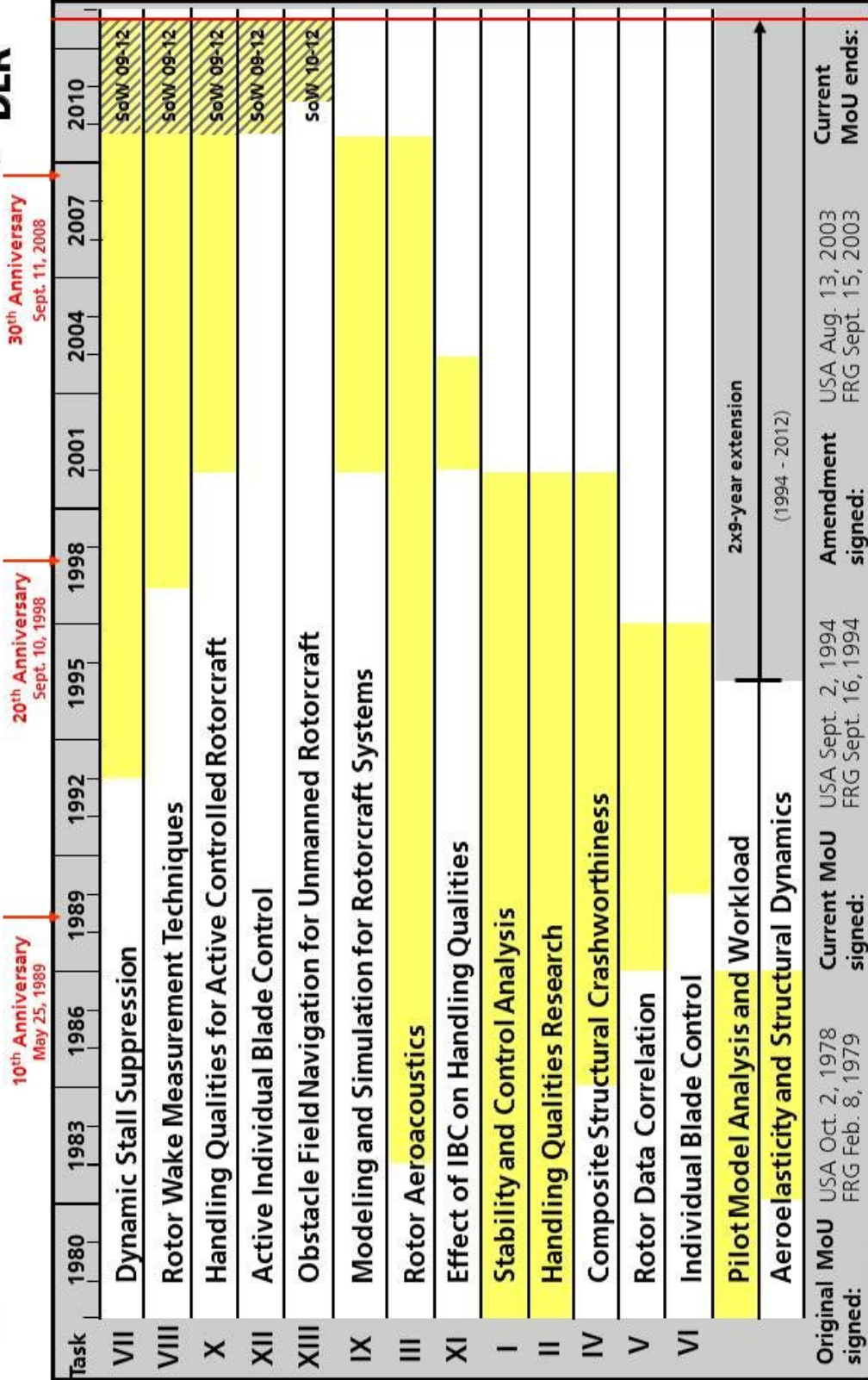
Special highlight meetings were the Anniversary Meetings:

10th Anniversary Meeting on May 25, 1989, at the Embassy of the Federal Republic of Germany in Washington, DC;

20th Anniversary Meeting on September 10, 1999, at the German Federal Ministry of Defense, Bonn, Germany;

30th Anniversary Meeting on September 11, 2008, at the Kemenate in Braunschweig, Germany.

The following figure summarizes the history of the U.S. / German MoU activities and the technical contents of the various tasks are described in detail in section 4.



3. MoU guidelines

The initial MoU had the general objective to develop the data base of helicopter flight control technology upon which it will be possible to establish handling qualities criteria and to address the tradeoffs among pilot workload, training requirements, mission effectiveness, cost, complexity, and reliability. This general objective was tailored into specific objectives based upon the identified applied research areas of common interests and benefits to both parties. For example, obtain solutions to problems that have been encountered in determining the stability and control characteristics that, combined with appropriate displays, allow adequate mission performance with tolerable aircrew workload and training within the minimum life cycle cost.

Statements of work were then defined and collaborative activities were emphasized. No money was exchanged. Twice a year (one in the US and one in Germany), technical meetings are held to review the progress, exchange ideas and data, and plan cooperative activities for the upcoming year. These technical meetings and related action items are documented by the country project officers through formal meeting minutes, which are distributed to the principal investigators and other government officials. In the course of working together over the years, other complementary activities, not directly related to flight control, have been discovered in which cooperation would be beneficial for both parties. These have resulted in agreements for additional tasks in rotorcraft structural dynamics and aero-elasticity, rotor acoustics, composite structural crashworthiness, rotor data correlation, dynamic stall suppression, and rotor wake measurement techniques. Recently, active individual blade control and obstacle field navigation for unmanned rotorcraft have been established as new tasks.

4. MoU Tasks Overview

During this nine-year period (2003-2012), there were seven active Tasks as illustrated in yellow highlight on the prior History and Evolution of the MoU figure. These include: rotor aeroacoustics (Task III); dynamic stall suppression (Task VII); rotor wake measurement techniques (Task VIII); modeling and simulation for rotorcraft systems (Task IX); handling qualities for active controlled rotorcraft (Task X); active individual blade control (Task XII); and obstacle field navigation for unmanned rotorcraft (Task XIII). Some of these Tasks were initiated before this nine-year period, while others were initiated only recently. For example, the rotor aeroacoustics Task was started in 1983, and obstacle field navigation for unmanned rotorcraft Task was started in 2010. Following is an overview of these seven Tasks.

4.1. *Task III: Rotor Aeroacoustics (2003-2009)*

Introduction: Rotorcraft external noise is critical to certification of helicopters, to the acceptance of rotorcraft in the public (sometimes severely restricting operations), to the detectability in military operations; and internal noise is annoying for pilots and passengers. The external noise is caused and influenced by many factors. Rotor rotational speed and blade tip Mach numbers are important for thickness noise and high-speed transonic impulsive noise. The specific loading of the rotor blades have an impact as well, and the flight condition. In contrast to fixed-wing aircraft, the blade tip vortices of rotorcraft form spirals in space that are engaged by other blades multiply and in different ways during the blade revolution. In the first and fourth quadrant of the revolution a parallelism of the blade leading edge and the tip vortices occurs. This causes strong impulsive blade-vortex interaction noise which happens in descending flight when these vortices are close to the passing blade or are even cut by them, and which represents one of the strongest noise radiation impact on ground.

Objectives: The physical understanding of noise generation and the development of noise avoidance and/or noise control means was the objective of this task. The focus was on designing higher harmonic and individual blade control systems noise reduction.

Approach: Since the early times of this MoU rotorcraft noise has been a permanent issue. Initially, the physics of noise generation, source identification and localization were the main goals and wind tunnel tests executed to generate the data required. Computer codes were written in parallel to predict rotor noise and the test data served for validation. Since 1994, when the first Higher Harmonic Control Aeroacoustic Rotor Test (HART) was commonly performed in the DNW wind tunnel using a model scale Bo105 rotor, active control strategies were investigated to explore possibilities to significantly reduce rotor blade-vortex interaction noise – one of the strongest sources occurring in descending flight. This was supported by Individual Blade control (IBC) testing of a full-scale Bo105 rotor at the NFAC in Ames. Very compre-

hensive data – including blade bending, blade motion, blade surface pressure and section aerodynamic loading, and noise radiation – were measured. These were completed by the HART II test in 2001 commonly performed again in the DNW using a Bo105 model rotor and extending the existing data base by extensive wake data, covering the overall geometry and the tip vortex inner structure.

Results: The experimental data brought deep insight into the physics and generated a deep understanding of the mechanisms of noise generation and especially the noise control using active blade root pitch control devices. The HART experiments made clear that it is not the blade moving away from the vortex when active control is applied, rather than it is the vortex moving away from the blade by as much as 10 times the blade tip deflection. The numerical tools were developed to model the physics and were validated with the experimental data. This allowed also prescribed wake codes to be applied for active blade control investigations, which is considered a significant enhancement of capabilities. Guidelines were developed for both comprehensive codes as well as coupled CFD/CSD approaches with minimum requirements for their set-up to be able to predict reliably the effects.

Payoff: The HART activities from 1994 until their end in 2012 were internationally recognized and the HART II data form a benchmark for code validation today. This is not only due to the numerous publications of the HART team, but also due to the establishment of a HART II International Workshop from 2005 to 2012 – jointly managed by US and German principal investigators – that opened a significant amount of data to the international rotorcraft community for the first time in the world. DLR and later NASA opened a web site for convenient download of data and all available documentation. The HART II activities generated more than 150 publications until the end of 2012, and three AHS Awards were given to the HART teams: the Grupo Agusta Award in 1996 for the HART Team; the Howard Hughes Award in 2004 for the HART II Team; and the AgustaWestland International Helicopter Fellowship Award in 2012 for the HART II International Workshop Team. The HART activities also paved the way for the next generation of active rotor blade control via active twist – again within an international cooperation. Another important pay-off is the advance in comprehensive code modeling that was only possible with the data commonly obtained.



Objectives

- Understand physics of noise radiation mechanisms of higher-harmonic controlled (HHC) rotors
- Develop/validate comprehensive codes and CFD/CSD coupling for BVI airload and noise prediction
- Explore the benefits of HHC for vibration and noise reduction

Technical Challenges

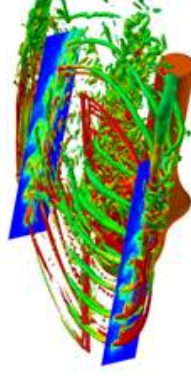
- Data analysis of HART II test (PIV, SPR, ...)
- Modeling wake perturbations due to HHC blade control within prescribed wake codes
- Preservation of vortical structures in CFD codes

Tasks \ Schedule

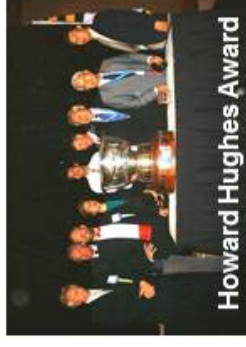
	CY	04	05	06	07	08	09
HART II data analysis							
Code validation							
HART II International Workshop							
Papers	★	★	★	★	★	★	★

Approach

Generation of comprehensive code models; mesh refinement and higher order models (CFD)



Computed wake structures



Howard Hughes Award

Major Milestones

AHS and ERF papers (03-12),
AHS Howard Hughes Award for HART II (04),
HART II International Workshop (05-12),
HART II Data Websites: DLR (05), NASA (09)

Contributions to Technical Objectives

Demonstrated significant improvement in comprehensive code and CFD/CSD coupling predictive capability by using HART II wind tunnel test database

4.2. Task VII: Dynamic Stall Suppression (2003-2012)

Introduction: Dynamic stall is an event occurring in highly loaded rotors, especially during maneuvers with high load factors, but also in high speed flight. It limits not only the flight envelope with respect to rotor loading and maximum speed, but also is a major source of structural loads of the rotor blades and the pitch links, as well a major source of vibrations and fatigue.

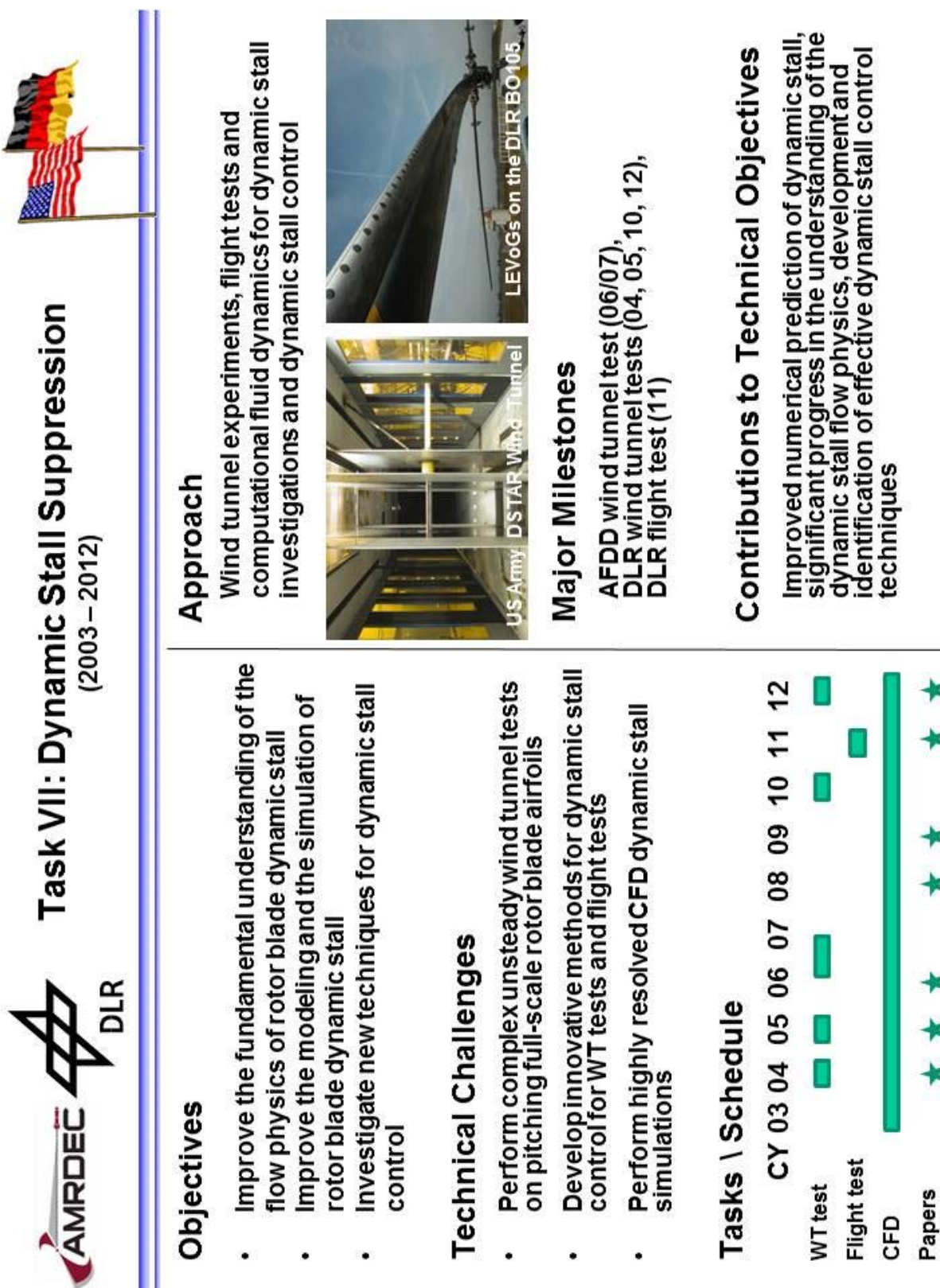
Objectives: The understanding of how stall develops, the ability to correctly predict stall and procedures or passive or active means to avoid and/or control stall effects is the subject of this task.

Approach: Since 1992, investigations into steady and dynamic stall have been addressed within this task. Steady and dynamic so-called 2D experiments with airfoil sections spanning the wind tunnel have been performed with different airfoils in wind tunnels on the US and German side. The models were instrumented with pressure sensors in the mid-section for analysis of the unsteady pressure distribution on upper and lower surface, providing the unsteady lift and pitching moment in attached and separated flow conditions. Additional measurements addressed the flow field off the surface via technologies developed in Task VIII, like particle image velocimetry (PIV), background oriented Schlieren (BOS) for density measurements, and hot film surface measurements for detection of laminar-turbulent transition in the boundary layer. Numerical simulations with the computational fluid dynamics (CFD) codes developed in the US and German organizations were performed and validated against experimental data. Passive and active means to alleviate stall effects were investigated numerically and experimentally.

Results: The validation of steady wind tunnel data with 2D numerical results of CFD codes revealed the importance of the wind tunnel wall interference. It was demonstrated that the central section, which was assumed to be purely 2D flow, is not only influenced by the presence of the upper and lower wall, but also by the actual 3D flow at the side walls connection to the airfoil. This led to a change in the numerical approach such as to perform 3D computations including all walls and covering the entire wind tunnel test section volume, including the small gap between the airfoil model and the side walls. Results obtained with this set-up were closest to the experimental data and the respective influence of upper and lower walls in 2D, as well as the side wall effects in a 3D computation could be quantified.

Payoff: The physics of dynamic stall are much better understood and requirements for both wind tunnel experiments as well as CFD simulation of these are defined now. Recent means to alleviate stall were investigated like leading edge vortex generators that influence the boundary layer in a 3D manner were demonstrated experimentally and numerically to delay stall effects to larger angles of attack. The close interaction with the development of measurement techniques (Task VIII) was found very fruitful

for this activity and the exchange of experimental and numerical data, especially the participation in the experiments were driving factors for the advance in this subject.



4.3. Task VIII: Rotor Wake Measurement Techniques (2003-2012)

Introduction: Due to the complexity of the flow field around a helicopter, helicopter aerodynamics deal with quite a number challenging aerodynamic problems comprising flow separation on the retreating blades, compressible flow with shocks embedded on the advancing blades, a complex wake structure contains strong blade tip vortices, unsteady loads due to fluid structure interaction, etc. Extreme operation conditions on rotor blades limit the helicopter in many respects, like maximum speed, efficiency, noise emissions, and loading capabilities. Due to the highly unsteady helicopter flow conditions, experimental investigations are required to complement numerical simulations even if considerable progress has been made recently in the development of the prediction capabilities for isolated helicopter components. With modern CFD methods it is possible to compute the unsteady, three-dimensional flow field around a helicopter under moderate operation conditions. The computation time needed for such a computation with high spatial and temporal resolution is excessive. Validation and detailed experiments are still needed to increase the physical understanding of helicopter flow phenomena and improve the modeling and prediction capabilities.

Objectives: Develop accurate and efficient techniques for exploring rotor wakes and identify those procedures and conventions needed to acquire, define, and interpret significant flow features. Ensure the extraction of valuable data for numerical prediction codes by the development of state-of-the-art measurement techniques and for their application in upcoming advanced-rotor testing (like the HART II follow-up STAR).

Approach: Establish a shared base of experience relating to the experimental study of vortex-dominated flows typical of rotor wakes. The activity will initially focus on the application of multiple-camera particle image velocimetry and the standards necessary for achieving quality measurements of three spatial velocity components in a volume (3C-3D-PIV). The measurement of the fourth, temporal component will also be investigated. Select data sets will be shared as required to critique procedures and validate results. Complimentarily, the partners will focus on multiple-camera background oriented Schlieren (BOS) and thermography techniques.

Results: A great number of successful PIV wind tunnel and flight test investigations of helicopter related aerodynamic problems have been performed within the past decade with an increasing tendency on both sides. Observation field sizes varies from 1mm^2 to several m^2 and spatial resolution varies from approximately 1 vector/cm to up to 100 vectors/mm. Velocity measurements can be performed simultaneously with density and blade deformation measurements at 2kHz with 1Mpx camera resolution. PIV measurements in small volumes (e.g. $5 \times 15 \times 15 \text{ cm}^3$) with up to 3.5 million instantaneously measured velocity vectors can be obtained by Tomographic PIV. Specific problems like particle void have to be addressed by the partners in close cooperation, especially when investigating rotating blade tip vortices.

Payoff: The physics of helicopter rotor wakes are much better understood and requirements for both wind tunnel experiments as well as CFD simulation of these are defined now. Recent means to alleviate pitch-up, BVI noise emission and vibrations were based on numerical computations and the codes were all validated by the results of measurement campaigns like HART II, which were performed by the partners individually or commonly. The close interaction with the aerodynamic and aeroacoustic MoU activities (e.g. Task III and Task VII) was found very fruitful for this activity and the exchange of experimental and numerical data, especially the participation in the experiments were driving factors for the advance in this subject. The partner demonstrated that their inventions of retro-reflective BOS and reference-free BOS are perfectly suited for large and full-scale and even in-flight studies owing to its fairly simple sensor units and robust, easy-to-use evaluation methods with a vast variety of future applications for studying maneuvering helicopters.



Objectives

- Develop accurate and efficient techniques for exploring rotor wakes to identify those procedures needed to acquire and interpret the significant vortex flow features
- Ensure the extraction of valuable data for numerical predictions by the development of state of the art measurement techniques

Technical Challenges

- Identification and characterization of measurement uncertainties of various optical rotor wake measurement techniques
- Select data sets to be shared as required to critique procedures and validate results
- Analysis and correlation of quantitative data for establishing a shared base of experience

Tasks \ Schedule

	CY	04	05	06	07	08	09	10	11	12
Flight test (DLR)										
RBOS WT test (NFAC)										
Conference papers	★	★	★	★	★	★	★	★	★	★
Journal papers	★									

Approach

Full-scale wind tunnel and flight testing with BOS, RBOS and SPIV (incl. high-speed and tomography techniques)



Major Milestones

Common Exp. Fluids paper on SPIV HART II (04)
SPIV flight tests (05) and Exp. Fluids paper (07)
NFAC RBOS test (10) and AHS paper (12)
BOS flight test (12) and AHS Journal paper (13)

Contributions to Technical Objectives

Demonstrated significant improvement in aerodynamic wind tunnel and flight test measurement capability and fidelity. Shared HO-TIS database for helicopter rotor wake characterization. TASK VIII development BOS is nowadays standard in major US and German wind tunnels.

4.4. Task IX: Modeling and Simulation for Rotorcraft Systems (2003-2009)

Introduction: The U.S. Army's Aeronautical Design Standard-33 (ADS-33) is a military rotorcraft handling qualities specification. Handling qualities are impacted by many ingredients, including: the task being performed; the vehicle stability and control; the usable cue environment available to the pilot; and environmental factors such as wind and turbulence. Performing a precision hover task on a calm clear-day is quite different (better task performance and easier) than performing the same task at night with a high level of wind and turbulence. Ground-based and in-flight simulation are efficient tools to study and understand the trade-offs of these ingredients and their effects on handling qualities. The fidelity in modeling these ingredients is important to ensure accurate results and trends across different facilities / test articles. One of the weak links has been the inclusion of turbulence. Turbulence models for helicopters which have been adopted from the fixed-wing community do not work well for the helicopter in the hover and low speed environment. ADS-33 includes requirements to assess the rotorcraft in winds and turbulence.

Objectives: The objective of this Task was to develop reliable helicopter models to support ground-based and in-flight simulation. This included the development of an EC 135 flight dynamics model for flight control design and in-flight simulation, and the development of a turbulence model for ground-based and in-flight simulation handling quality studies.

Approach: The approach for this Task was to perform system identification and analysis to extract models; exchange aircraft models and flight data; develop empirical hover/low-speed turbulence models; investigate generalization of the turbulence models; and then document the results. Flight tests were performed in the U.S. with an instrumented UH-60 Black Hawk and Yamaha R-MAX, and in Germany with an instrumented EC 135 having a Fenestron type tail rotor, while pre-tests were performed with an instrumented BO 105 helicopter, having a conventional tail rotor. Data was collected in various wind and turbulence conditions and turbulence models were extracted using sophisticated system identification and model inversion techniques. The method uses aircraft angular and vertical rates obtained from flight tests in atmospheric turbulence and a math model of the aircraft dynamics to extract equivalent control disturbances. These control disturbances are the control inputs required to generate aircraft angular and vertical rates in calm conditions that are consistent with rates observed in flight in atmospheric turbulence. During the analysis and development of the models, a German professor came to the U.S. to collaborate with the U.S. principal investigator (PI). Also, the U.S. PI received his PhD conducting research for this Task. From the flight tests with multiple size rotorcrafts, a generalized turbulence model can be developed.

Results: This modeling approach has successfully been used to develop hover/low-speed turbulence models for both the UH-60 and the EC135. These models, called Control Equivalent Turbulence Input (CETI) models, were implemented and evaluated in ground-based simulations and in-flight simulators both in the U.S. and Germany. Results from piloted evaluations show that the effects of atmospheric turbulence on a hovering rotorcraft can be effectively simulated using the Control Equivalent Turbulence Input modeling method. In addition, high fidelity math-models that include higher-order effects are required for accurate extraction of control equivalent turbulence inputs for this type of turbulence modeling. The CETI turbulence model was implemented during the evaluation of several ADS-33 flight test maneuvers, or mission task elements (MTEs). The presence of simulated turbulence during the evaluations of three ADS-33 MTEs resulted in a degradation of handling qualities ranging from one-half to two ratings, primarily due to an increase in station keeping workload. This highlights the importance of including the effects of turbulence in handling quality research.

Payoff: Having the validated, explicit helicopter hover / low-speed turbulence model is providing many payoffs. For control system design, including the effects of turbulence in disturbance rejection bandwidth analysis / evaluation is critical. For handling quality research, the CETI turbulence model is being used providing more realistic and challenging environments for quantifying handling quality boundaries.



Approach

- development of flight dynamics model for the EC 135 helicopter
- development of a turbulence model for single main rotor helicopters

Technical Challenges

- **Extracting a math model of the highly complex EC-135 helicopter dynamics**
- **Development of high fidelity stable inverse aircraft math models including coupling**
- **Obtaining accurate measurements of atmospheric characteristics at the aircraft during flight testing**

Tasks | Schedule



Flight testing in atmospheric turbulence with the RASCAL (53.7 ft rotor), ACT/FHS (33.4 ft rotor) and RMAX (10.3 ft rotor)



Major Milestones

RASCAL flight tests (04, 07), ACT/FHS flight tests (04, 07, 08), RMAX flight tests (05), turbulence model used in VMS simulation study (08) and 7 papers/reports published

Contributions to Technical Objectives

Developed high fidelity flight dynamics model of the EC-135, and a single-main rotor Control Equivalent Turbulence Input (CETI) model. CETI model published and widely utilized in research and development studies conducted by industry, academia and government.

4.5. Task X: Handling Qualities for Active Controlled Rotorcraft (2003-2012)

During this nine-year period, three important technical topics have been investigated: an assessment of ADS-33 using a large single-main rotor helicopter (CH-53G); helicopter flight control stability margins; and active inceptors. Each technical topic is discussed below:

Assessment of ADS-33 using a CH-53G

Introduction: In the early 1980's, a major revision and update of the military helicopter flying qualities specification MIL-H-8501A, which was also used in Germany, was initiated by the U.S. Army Aeroflightdynamics Directorate (AFDD). It was recognized that the increasing demands resulting from the continuous extension of helicopter mission scenarios towards operations at night and/or in other degraded visual conditions, in nap-of-the-Earth (NOE) flight, and in tasks that involve precise tracking of targets and landing in unprepared areas close to obstacles, significantly influence the handling qualities (HQs) required. MIL-H-8501A did not account for these increasing demands. In the following years, numerous organizations and individuals contributed to the modern helicopter handling quality requirements with theoretical analysis, piloted simulations, and flight tests. The proposed criteria and the associated boundaries were studied continuously and adopted if necessary. There are numerous international publications available covering the last thirty years of research on rotorcraft handling qualities. Many results were incorporated into a new updated specification that became the U.S. Army Aeronautical Design Standard 33, ADS-33. The latest version was released in March 2000 and is denoted ADS-33E-PRF. Since the main focus of the work that supported the first versions of ADS-33 was on scout and attack missions, requirements for cargo helicopters and operations with external loads were not addressed. To fill this gap the U.S. Army conducted flight tests in the 1990's with a Boeing CH-47D, a tandem-rotor cargo helicopter. The results were incorporated in the E-version of ADS-33. It was explicitly recommended to undertake a comparable evaluation with a single-rotor production cargo helicopter to corroborate the findings of the CH-47D tests and identify any fundamental differences or tandem rotor biases.

Objectives: The tests were performed to evaluate the applicability and repeatability of cargo helicopter handling qualities requirements as defined in the U.S. Army's Aeronautical Design Standard (ADS)-33E-PRF. The objectives were to corroborate earlier findings and to propose modifications if deemed necessary. The CH-53G was chosen because it is the largest helicopter operated by the German Army and its dedicated role is cargo and troop transport.



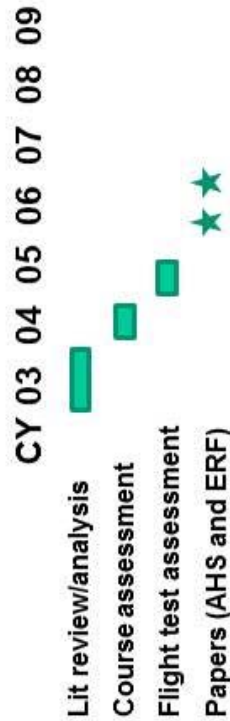
Objectives

- Expand handling quality (HQ) database for cargo helicopters
- Verify ADS-33E cargo helicopter criteria (results of CH-47D tests) for single main rotor helicopter
- Effect of aircraft size on stability & DRB reqmts

Technical Challenges

- Aircraft/data gathering system preparation; test matrix definition
- ADS-33 course set-up / calibration
- Analysis and correlation of qualitative and quantitative data

Tasks \ Schedule



Approach

- Perform ADS-33 assessment with German Armed Forces Sikorsky CH-53G at WTD 61



Major Milestones

- Flight tests (04-05); AHS & ERF papers (06)

Contributions to Technical Objectives

- ADS-33 Maneuvers deemed appropriate:
 - Hover, Lateral Reposition, Depart/Abort, Pirouette
- ADS-33 Maneuvers proposed for revision:
 - Hover Turn, Vertical, Slalom, Slope/Landing
- CH-47D ADS-33 test results were largely confirmed
- Predictive HQ (quantitative) criteria and assigned HQ (qualitative) criteria show good agreement

Approach: Toward extending the handling quality database for larger helicopters and to gather experience in modern handling quality testing methods with larger transport helicopters in Germany, a flight test assessment with a German Army Sikorsky CH-53G was conducted. The German Aerospace Center DLR was tasked with the test organization and data analysis. The tests were conducted at the German Army Technical and Airworthiness Center for Aircraft (WTD 61). Under the framework of the MoU, a NASA test pilot and a U.S. Army engineer participated and added invaluable support.

Results: The quantitative criteria and the associated boundaries as specified in the standard were largely confirmed. The test results and pilots' comments indicate that the requirements for roll agility can be relaxed. Several flight test maneuvers were revised and tailored. Generally the heights for performing the near-earth maneuvers were increased. The time/tolerances experienced were borderline desired/adequate or adequate.

Payoff: Results from this collaborative test has solidified the ADS-33 requirements for cargo helicopters and highlighted the sensitivity and need to tailor the requirements in ADS-33 for larger rotorcraft. This has impacted the CH-53K procurement and will influence Future Vertical Lift (FVL) requirements in the U.S. In Germany, these results will influence the acquisition of the Future Transport Helicopter.

Rotorcraft Flight Control Stability Margins

Introduction: Rotorcraft flight control system design must meet numerous criteria for military procurement, which often translate to design guidelines for civilian aircraft, as well. The handling qualities requirements may include criteria from MIL-H-8501 or more recently, from the U.S. Army's Aeronautical Design Standard-33 (ADS-33). The control system requirements of MIL-F-9490D include criteria for system stability. Notable are the requirements for 45-degree phase margin at the crossover response frequency and 6 dB gain margin at the 180-degree phase angle crossing. These stability requirements help ensure the flight control system is robust and it has some margin against degradation due to uncertainties or degradation in vehicle characteristics over its life. In addition, the stability requirements are aimed at keeping adverse dynamics from the rotor system, airframe structural response, and/or external slung load dynamics outside of (or not objectionable within) the pilot's nominal frequency range. This also implies the overall system response is well behaved to noise and disturbances. The current flight control system stability requirements in MIL-F-9490D are not well supported with data, but are generally based on historical rules-of-thumb.

Objectives: There is an important trade-off in the control system design where increases in disturbance rejection bandwidth (DRB) can only be met by decreasing stability margins. As rotorcraft size and flight control system complexity increase,

these stability criteria bounds have proven more difficult to meet, while maintaining disturbance rejection performance. Indeed, current and developing aircraft designs have sought relief from these criteria. Also, a projected new class of very heavy lift rotorcraft designs will further strain the ability to meet the stability margin criteria. Not meeting these requirements can have airworthiness implications. It is recognized that stability margins are necessary, but the question is: what are appropriate margins?

Approach: To help answer this question, from a handling qualities standpoint, a collaborative piloted-simulation study was conducted using the NASA-Ames Vertical Motion Simulator to investigate control system stability criteria for a range of rotorcraft sizes. The experiment concentrated on hover and low speed tasks and requirements. Four aircraft configurations were investigated: the UH-60, which can serve as a flight test anchor point, H-53 with and without a slung load, and a large tiltrotor with rotors fixed at the hover angle. Four stability margin / disturbance rejection bandwidth design points were investigated. Ten pilots, including a pilot from WTD 61, flew over 2,000 data runs with evaluation comments and objective performance data recorded.

Results: A summary of the overall results found that for all the aircraft configurations, low-phase margin (20-23 degrees) was unanimously rated as oscillatory, and prone to pilot-induced-oscillations (PIOs), and was objectionable. For the H-60 class helicopter, the 9490 stability margins of 45-degrees and 6 dB were preferred. For the H-53 class helicopter, the pilots preferred a trade-off of higher disturbance rejection bandwidth (DRB) for lower stability margins (38-degrees of phase margin). For the LCTR class tiltrotor, the pilots preferred an even more relaxed stability margins (31-37 degrees) for even higher DRB. Additionally, it was found that some of the ADS-33 Hover maneuver performance standards needed to be modified for the large size of the LCTR, and the ADS-33 yaw bandwidth requirements need modifying to account for the large pilot off-set from the aircraft center of gravity in the LCTR design.

Payoff: These results provide important substantiation data to support flight control margins and disturbance rejection bandwidth requirements, and critical insights into ADS-33 refinements for larger vehicles. This is extremely important from a design and “smart-buyer” standpoint as both countries move toward acquiring larger rotorcraft, the Future Vertical Lift in the U.S. and the Future Transport Helicopter in Germany.

Active Inceptors

Introduction: For the majority of current helicopters, the force-feel system characteristics of the cyclic inceptors are set based on the characteristics of the mechanical components in the control system (mass, springs, friction dampers, etc.). For these helicopters, the pilot typically has one set of cyclic feel characteristics to use over the entire flight envelope, with perhaps a trim release to minimize control forces while maneuvering. With the advent of fly-by-wire control systems and active inceptors in helicopters, the force feel characteristics are now determined by the closed-loop response of the active inceptor itself as defined by the inertia, force/displacement gradient, damping, breakout force and detent shape configuration parameters in the inceptor control laws. These systems give the flexibility to dynamically prescribe different feel characteristics for different control modes or flight conditions.

They also give the ability to provide tactile cueing to the pilot through the actively controlled side-stick or center-stick cyclic inceptor. A number of studies have been conducted to assess the impact of controller force-feel characteristics on the pilot-vehicle flying qualities in high performance fixed wing fly-by-wire aircraft, primarily directed toward minimizing pilot induced oscillations and roll ratcheting. Research into the effects of feel-system characteristics on rotorcraft handling qualities is much sparser.

Objectives: Under Task X, Handling Qualities for Active Controlled Rotorcraft, of the U.S. German Memorandum of Understanding for cooperative research on helicopter aeromechanics, the objective of this work is to collect flight test data to correlate changes in cyclic inceptor force-feel characteristics with piloted handling qualities, and to use this data to evaluate existing, or provide a basis for developing new handling qualities criterion that account for the cyclic inceptor force-feel characteristics.

Approach: The approach for this collaborative work was to use each countries ground-based and in-flight simulator to perform systematic evaluations of a variety of force-feel characteristics while performing meaningful handling quality tasks. In Germany, this entails flight tests on DLR's ACT/FHS variable-stability helicopter and in the U.S., this entails flight tests on AFDD's RASCAL variable-stability helicopter. In addition, the NASA-Ames ground-based Vertical Motion Simulator (VMS) was used to evaluate force-feel characteristics for a variety of configurations and tasks. This approach enabled two types of inceptors to be assessed: a long-pole center stick in the U.S. and a short-pole side stick in Germany. The VMS simulation had both. Handling quality tasks from ADS-33 served as evaluation tasks. Parameters to be investigated included the stick characteristics (damping, breakout, gradient, inertia, natural frequency, and control-response type (rate versus attitude command)).

Task X: Handling Qualities for Active Controlled Rotorcraft

Active Inceptor (2009 – 2012)



Objectives

- Study the interaction between active inceptor force-feel characteristics and handling qualities
- Evaluate/develop handling qualities criteria for active inceptors
- Explore the benefits of tactile cueing

Technical Challenges

- Identification and characterization of active inceptor dynamic system capabilities
- Analysis and correlation of qualitative and quantitative data
- Identification and mapping of tactile cues for carefree maneuvering

Tasks \ Schedule

CY 04 05 06 07 08 09 10 11 12

Flight test (Ames)

Flight test (WTD-61)

VMS Simulation

Papers



Approach

Flight testing with active long-pole center stick on RASCAL and side-stick on ACT/FHS



Major Milestones

RASCAL flight tests (10-11) and AHS paper (12), ACT/FHS flight tests (11) and ERF paper (12), VMS simulation study (12) and AHS paper (13)

Contributions to Technical Objectives

Demonstrated significant improvement in handling qualities with changes in inceptor force-feel characteristics, assessed current ADS-33 criteria against flight test database

Results: A flight test evaluation of the interaction between cyclic inceptor force-feel characteristics and rotorcraft handling qualities has been performed with a center stick on AFDD's RASCAL, and with a side-stick on DLR's EC 135 ACT/FHS. Based on the results of these test, the following conclusions are drawn:

1. The effect of cyclic force-feel characteristics have been shown to have a significant impact on the handling qualities of rotorcraft.
2. In forward flight, different test maneuvers (Roll Handling Task and Slalom MTE) show comparable results.
3. Whereas the side-stick shows differences between Rate and Attitude Command, there is no significant difference for the center stick.
4. For the Attitude Command response type, the improvement points to higher damping to frequency ratios for the center stick than for the side-stick. This means the side-stick should be more agile than the center stick for the AC response type.
5. For the Rate Command response type, this effect is significantly larger. So an even more agile stick characteristic is preferred for the side-stick.
6. Pilot model analyses may explain the trend to lower damping for side-sticks as a consequence of different armrest positions compared to center sticks and its effect on pilot control dynamics.
7. Meeting the current ADS-33E Level 1 bandwidth requirements from force inputs is not sufficient to ensure Level 1 handling qualities for both inceptor types.

Payoff: The results from this collaborative study will define inceptor force-feel requirements for updates to ADS-33, will help define inceptor design guidance for future rotorcraft, and will establish a sound database for subsequent inceptor studies. This is very important as the rotorcraft industry moves toward fly-by-wire/light control systems, enabling active inceptors for cueing and task-tailored control laws. In addition, there may be some advantages to changing the inceptor force-feel characteristics to help deal with aircraft failure modes.

4.6. Task XII: Active Individual Blade Control (2009-2012)

Introduction: Active blade control has been a subject of interest since 1989 within the former Task VI (Individual Blade Control, this included Bo105 full-scale main rotor tests in the Ames full-scale wind tunnel) and the Higher Harmonic Control activities of the former Task III (Rotor Aeroacoustics) from 1992 until its end. A new technology, different from blade root control concepts such as IBC or HHC, is the active twist of the rotor blades using piezo-electric actuators embedded in the skin of the blades. This provides full IBC capability using static and dynamic twist of the blades without any mechanical devices.

Objectives: As a successor of Task III, this task aims at exploring the active twist technology as a potential candidate of future rotorcraft extended control capabilities, including the classical subjects of vibration, noise and power reduction. The active twist technology also aims at individual blade tracking during flight, adaptation of the steady twist to the operational condition, improving the hover figure of merit, and support of the pilot control.

Approach: A four-bladed Mach scale articulated model rotor with active twist capability has been built at DLR. Within Task XII, numerical simulations to explore the benefits and limitations of active twist with respect to the various objectives have been performed. After a preliminary hovering test at DLR in January/February 2013, a common DNW wind tunnel test is under preparation (currently scheduled for November 2013) within the international STAR (Smart Twisting Active Rotor) cooperation. The model rotor is highly instrumented with more than 150 absolute pressure sensors, numerous strain gauges, and other sensors. This comprehensive data base includes air data from DNW, noise radiation measurements and PIV measurements, benefitting from the activities of Task VIII and their involvement in the experiment.

Results: Similar to the HART tests of 1994 and 2001, the STAR test executed within this Task will provide a large and comprehensive data base useful for evaluation of this active twist technology in hover, low speed descent, cruise, high speed, high load in cruise, and even at half rotating speed in high advance ratio conditions. This allows for validation of all physical relevant elements of rotor simulation and prediction, which has been successfully done for HHC and IBC technology within Task III in the past. Numerical studies based on blade design data and on measured blade properties are performed to support the wind tunnel test and to identify test conditions of maximum active twist control benefits.

Payoff: The international cooperation with its work share in computational efforts and cost-share for the wind tunnel test allows every partner access to the full data base at a minimum of individual effort. This is a typical example of the benefits of such cooperation. Several years of exclusive data usage (to partners only) will allow for numerous publications both based on the experimental data as well as on code validation.



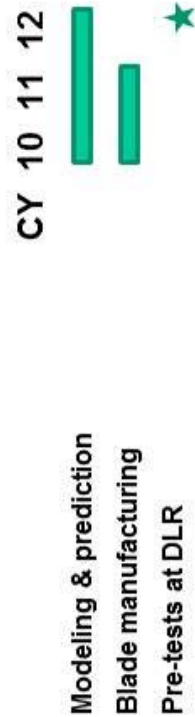
Objectives

- Understand physics of active twist controlled rotors
- Prepare and perform active twist rotor test in the DNW
- Explore the benefits of active twist control for vibration and noise reduction

Technical Challenges

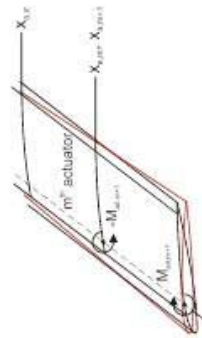
- Manufacturing of active twist rotor blades
- Modeling twist actuation in rotor codes
- Pre-testing of active twist rotor at DLR

Tasks \ Schedule



Approach

Blade design and manufacturing; numerical evaluation of active twist benefits



Modeling twist actuation



Hover pre-test

Major Milestones

Manufacturing of active twist blades (10-11),
Lab and whirl tower tests (12),
Hover pre-test (12-13),
Test matrix definition and prioritization (10-12)

Contributions to Technical Objectives

Evaluation of over 300 test conditions for the DNW test matrix, identification of the most relevant conditions, applicability of advanced measurement techniques

4.7. Task XIII: Obstacle Field Navigation for Unmanned Rotorcraft (2010-2012)

Introduction: Increased use of Unmanned Aerial Systems (UAS), including unmanned rotorcraft, has brought about an increased need for higher levels of autonomy in complex and urban environments. In these environments, autonomous obstacle field navigation (OFN) will be essential for successful mission completion. Both the AFDD and DLR are working on OFN algorithms for unmanned helicopters. Being able to define and measure the performance of these OFN navigation guidance algorithms is fundamental for the development, improvement, and optimization of these algorithms.

Objectives: This Task seeks to provide a means of assessing obstacle field navigation solutions being developed in the U.S. and Germany, thus providing a broader understanding of the solution methods and performance tradeoffs. A set of benchmarks will be developed to provide a fixed point, or a baseline, against which to measure performance.

Approach: The benchmarks include the following elements: a *simple terrain* of six simple geometries with each case having two or fewer obstacles and a ground plane; an *urban terrain* representing a high resolution height map of downtown San Diego captured from publicly-available LIDAR scan; *vehicle dynamics model* consisting of speed and acceleration limits, and minimum allowable obstacle clearance; and *performance metrics* used to measure performance and report the results. Given these, the overall vehicle guidance task is to arrive at the mission goal while complying with the vehicle dynamic model in a way that minimizes the performance criteria and does not violate constraints. Trajectory duration is the quantity that needs to be minimized and the dynamic limits and terrain clearance represent constraints that need to be followed. The overall work in this Task is divided into two phases. The first phase (2010-2012) is to produce OFN results for a common set of *simple terrain* geometries. The second phase (to be conducted under the new PA) seeks to produce results for a more complex terrain, first in simulation and then in flight test.

Results: In Germany, the DLR research for their Autonomous Rotorcraft Testbed for Intelligent Systems (ARTIS) platform has focused on maximizing onboard information processing and decision-making in conjunction with the operator. The decision-making is performed in two stages or steps, and is combined in the Mission Planning and Execution (MiPIEx) software. The results indicate that MiPIEx achieved trajectory duration within 16.6% of the baseline cases for the simple terrain set when using an AFDD style sensor. It has less extreme acceleration but higher turn rates, resulting in some speed losses. MiPIEx runs in real time, and re-plans in a fraction of the time it takes for the initial plan. MiPIEx worked significantly better with the LIDAR sensor model, with its wide-angle field of view and longer detection range of 70 m, in comparison to the stereo camera model with narrower field of view and restricted range of 43 m. In the U.S., the AFDD research for their Autonomous Rotorcraft Project fo-

cused on planning that assumes obstacle locations are poorly or incorrectly known in advance, and relies on sensor updates to provide safe planning. AFDD's most recent planner, RiskMinOFN, is designed to limit exposure to risks due to uncertainty and other arbitrary factors. RiskMinOFN uses an evidence grid in the form of a three-dimensional array to store terrain and empty space data. This terrain is shifted along with the vehicle position without storing information that page off the array. RiskMinOFN performs within 10% of baseline durations for the simple terrain set and 5% for the urban set. In urban terrain, RiskMinOFN trajectories use less extreme acceleration and turning rate compared to the baseline, resulting in smoother paths.

Payoff: The phase one results have benefited both DLR and AFDD by allowing them to optimize their planners against a known baseline, and by providing a means to measure performance. The benchmarking provides a quantitative performance measurement of the effects of even a small change to the planner. The metrics developed tell meaningful things about speed, smoothness, and safety, and are useful to tell whether the trajectory fails to meet all the benchmark criteria. They are also useful for making quantitative statements of planner performance over long missions. These properties are useful for tuning parameters and optimizing the design of a particular planner. Having a benchmark also allows researchers to study the effect of changing sensor properties on autonomous flight performance. Both German and U.S. researchers have used the benchmark and metrics for improving their algorithms and have seen substantial performance benefits over the time of this collaboration.



Task XIII: Obstacle Field Navigation Benchmarking and Metrics (2010 – 2012)



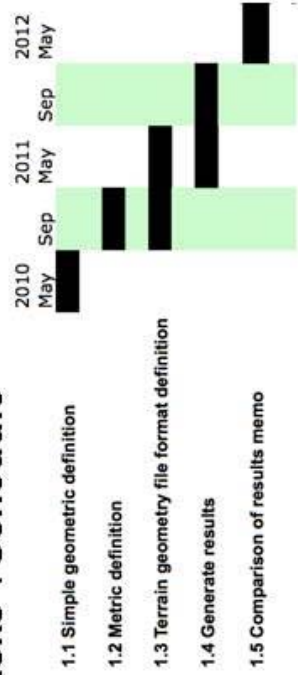
Objectives

- Provide a means to assess obstacle field navigation solutions
- Provide a broader understanding of solution methods and performance tradeoffs

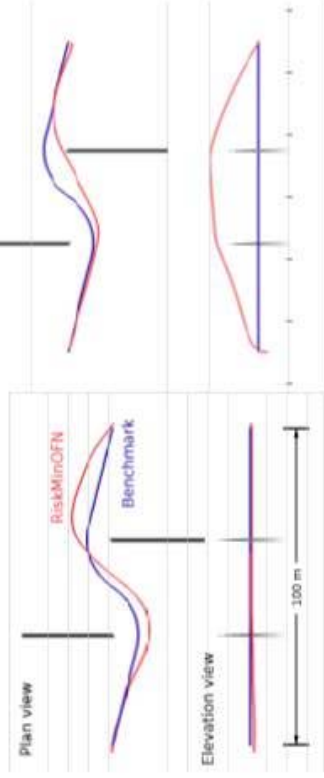
Technical Challenges

- Selection of benchmark tasks, including obstacle geometries divided into simple cases and urban cases
- Definition and selection of trajectory metrics
- Simulation of obstacle field navigation, and exchange of solution trajectories
- Exchange of LADAR scans from test sites

Tasks \ Schedule



Approach



US (left) and German (right) solutions compared to a common baseline solution (blue)

Major Milestones

Comparison of results memorandum (2012)

Contributions to Technical Objectives

Ability to assess solutions demonstrated by US and Germany in simple and complex environments
Collaboration has resulted in more meaningful metrics
Broader understanding shown through performance improvements of US and German solutions over time

5. Future

The US/German MoU has generated not only a lot of knowledge on both sides, visible by the numerous publications at conferences and in archival peer-review journals. The quality of research also was highlighted by several prestigious AHS Awards. Frequent exchange of personal in both directions to assist the partner organization during flight or wind tunnel testing was always a reliable foundation and a further reason for success. Several scientists stayed abroad for longer times to perform research at the other organization, adding to the value of the cooperation. The knowledge gained and its frequent exchange proved to be a major benefit for both parties.

In addition, the long-term collaboration of scientists in both countries has brought friendship that continued on a private basis after closure of tasks. It is this deeper understanding that made this MoU special and outstanding over other cooperations.

Currently negotiations are underway to continue this extra-ordinary cooperation under a Project Agreement and to bring it into the next decade.

6. Bibliography

The minutes of the MoU Meetings have been published in reports with limited distribution. This list refers only selected papers and reports which are highly related to the activities conducted under this MoU during the nine years period.

Task III- Rotor Aeroacoustics (2003-2009)

- [1] Lim, Joon W., van der Wall, Berend G.: Investigation of the Effect of a Multiple Trailer Wake Model for Descending Flights, 61st Annual Forum of the AHS, Grapevine, TX, 2005
- [2] Lim, Joon W., Nygaard, Tor A., Strawn, Roger, Potsdam, Mark: BVI Airloads Prediction Using CFD/CSD Loose Coupling, 4th AHS Vertical Lift Aircraft Design Conference, San Francisco, CA, 2006
- [3] Schneider, Oliver, van der Wall, Berend G.: Conditionally Averaging of Pressure Data from HART II, DLR IB 111-2006/08, 2006
- [4] van der Wall, Berend G., Richard, Hugues: Analysis methodology for 3C PIV data of rotary wing vortices, Experiments in Fluids, Vol. 40, No. 5, pp. 798-812, 2006
- [5] Sim, Ben W., Lim, Joon W.: Blade-Vortex Interaction (BVI) Noise & Airload Prediction using loose Aerodynamic/Structural Coupling, 62nd Annual Forum of the AHS, Phoenix, AZ, 2006
- [6] Richard, Hugues, van der Wall, Berend G.: Detailed investigation of rotor blade tip vortex in hover condition by 2C and 3C PIV, 32nd European Rotorcraft Forum, Maastricht, Netherlands, 2006
- [7] van der Wall, Berend G.: Mode identification and data synthesis of HART II blade deflection data, DLR-IB 111-2007/28, 2007
- [8] van der Wall, Berend G.: Mode identification and data synthesis of HART II blade deflection data - part II, DLR-IB 111-2007/33, 2007
- [9] Riemenschneider, Johannes, Wierach, Peter, Optiz, Steffen: Testing and Simulation of an Active Twist Rotor Blade, Adaptronic Congress, Göttingen, Germany, 2007
- [10] van der Wall, Berend G., Schneider, Oliver: Conditional Averaging Methodology for Periodic Data with Time Jitter and Spatial Scatter, 33rd European Rotorcraft Forum, Kazan, Russia, 2007

- [11] Wierach, Peter, Riemenschneider, Johannes, Opitz, Steffen, Hoffmann, Frauke: Experimental Investigation of an Active Twist Rotor under Centrifugal Loads, 33rd European Rotorcraft Forum, Kazan, Russia, 2007
- [12] Schneider, Oliver, van der Wall, Berend G.: Comparison of Simple and Conditional Averaging Methodology Based on Results of the HART II Wind Tunnel Test, International Forum on Rotorcraft Multidisciplinary Technology, Seoul, Korea, 2007
- [13] van der Wall, Berend G., Richard, Hugues: Hover Tip Vortex Structure Test (HOTIS) - Test Documentation and Representative Results -, DLR-IB 111-2008/16, 2008
- [14] Monner, Hans P., Opitz, Steffen, Riemenschneider, Johannes, Wierach, Peter: Evolution of Active Twist Rotor Designs at DLR, 16th AIAA/ASME/AHS Adaptive Structures Conference, Schaumburg, IL, 2008
- [15] Lim, Joon W.: An Assessment of Rotor Dynamics Correlation for Descending Flight Using CFD/CSD Coupled Analysis, 64th Annual Forum of the AHS, Montréal, Canada, 2008
- [16] Lim, Joon W., Strawn, Roger: Computational Modeling of HART II Blade-Vortex Interaction Loading and wake System, Journal of Aircraft, 45 (3), 2008.
- [17] Hoffmann, Frauke, Opitz, Steffen, Riemenschneider, Johannes: Validation of Active Twist Modeling Based on Whirl Tower Tests, 65th Annual Forum of the AHS, Grapevine, TX, 2009
- [18] van der Wall, Berend G., Yin, Jianping: Simulation of Active Rotor Control by Comprehensive Rotor Code with Prescribed Wake using HART II Data, 65th Annual Forum of the AHS, Grapevine, TX, 2009
- [19] van der Wall, Berend G.: The Data Base of the HART II International Workshop, Indian Institute of Science Centenary International Conference and Exhibition on Aerospace Engineering, Bangalore, India, 2009

Task VII – Dynamic Stall Suppression (2003-2012)

- [20] Geißler, Wolfgang, Dietz, Guido, Mai, Holger: Dynamic Stall and its Passive Control Investigations on the OA209 Airfoil Section, 31st European Rotorcraft Forum, Florence, Italy, 2005
- [21] Mai, Holger, Dietz, Guido, Geißler, Wolfgang, Richter, Kai, Bosbach, J., Richard, Hugues, de Groot, Klaus: Dynamic Stall Control by Leading Edge Vortex Generators, 62nd Annual Forum of the AHS, Phoenix, 2006

- [22] Gardner, Anthony D., Richter, Kai, Rosemann, Henning: Simulation of Oscillating Airfoils and Moving Flaps Employing the DLR-TAU Unsteady Grid Adaptation. In: Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 96, C. Tropea, S. Jakirlic, H.-J. Heinemann, R. Henke, H. Hönliger, Springer: Berlin Heidelberg New York, 2007
- [23] Mai, Holger, Dietz, Guido, Geissler, Wolfgang, Richter, Kai, Bosbach, Johannes, Richard, Hugues, de Groot, Klaus: Dynamic stall control by leading edge vortex generators. Journal of the American Helicopter Society, 53 (1), pp. 26 - 36, 2008, ISSN 0002-8711
- [24] Raffel, Markus, Richard, Hugues, Richter, Kai, Bosbach, Johannes, Geißler, Wolfgang: Pitching Airfoil Boundary Layer Investigations, 12th International Symposium on Flow Visualization, Göttingen, Germany, 2006
- [25] Richter, Kai, Le Pape, Armin, Knopp, T., Costes, Michel, Gleize, V., Gardner, Anthony D.: Improved Two-Dimensional Dynamic Stall Prediction with Structured and Hybrid Numerical Methods, 65th Annual Forum of the AHS, Grapevine, TX, 2009
- [26] Gardner, Anthony D., Richter, Kai, Rosemann, Henning: Numerical Investigation Of Air Jets For Dynamic Stall Control On The OA209 Airfoil, 36th European Rotorcraft Forum, Paris, France, 2010
- [27] Le Pape, Armin, Richter, Kai, Knopp, T., Costes, Michel, Gleize, V., Gardner, Anthony D.: Validation of Structured and Hybrid Numerical Methods for Improved Two-Dimensional Dynamic Stall Prediction, Onera/DLR Aerospace Symposium (ODAS), Berlin, Germany, 2009
- [28] Gardner, Anthony D.: Numerical Investigation of Air Jets for Dynamic Stall Control on the OA209 Airfoil, DLR IB 224-2009 A32, 2009
- [29] Heine, Benjamin, Mulleners, Karen, Gardner, Anthony D., Mai, Holger: On the Effects of Leading Edge Vortex Generators on an OA209 Airfoil, Onera/DLR Aerospace Symposium (ODAS), Berlin, Germany, 2009
- [30] Heine, Benjamin, Schwermer, T., Raffel, Markus: The Effect of Vortex Generators on the Flow around a Circular Cylinder, 15th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 2010
- [31] Mulleners, Karen, Raffel, Markus: A Time-resolved Dynamic Stall Investigation based On Coherent Structure Analysis, 15th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 2010
- [32] Mulleners, Karen, Raffel, Markus: The Onset of Dynamic Stall: a Time-resolved Approach, 36th European Rotorcraft Forum, Paris, France, 2010

- [33] Heine, Benjamin, Mulleners, Karen, Joubert, G., Raffel, Markus: Dynamic stall control by passive disturbance generators, 29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, 2011
- [34] Kindler, Kolja, Mulleners, Karen, Raffel, Markus: Dynamic Stall on a Fully Equipped Helicopter Model, 36th European Rotorcraft Forum, Paris, France, 2010
- [35] Mulleners, Karen: On the Coherent Structures behind the Phenomenon of Dynamic Stall, Dissertation, DLR-FB 2010-22, 2010
- [36] Mulleners, Karen, Raffel, Markus: The Onset of Dynamic Stall: a Time-Resolved Approach, 36th European Rotorcraft Forum, Paris, France, 2010
- [37] Richter, Kai, Rosemann, Henning: Numerical Simulation of Wind Tunnel Wall Effects on the Transonic Flow about the VC-Opt Airfoil in DNW-TWG, 17th DGLR-Fach-Symposium der STAB, Berlin, Germany, 2010
- [38] Richter, Kai: Untersuchungen zur Aerodynamik von Miniature Trailing-Edge Devices in transsonischen Strömungen, Dissertation, DLR-FB 2010-15, 2010
- [39] Gardner, Anthony D., Knopp, T., Richter, Kai, Rosemann, Hennig: Numerical Investigation of Pulsed Air Jets for Dynamic Stall Control on the OA209 Airfoil, 17th DGLR-Fach Symposium der STAB, Berlin, Germany, 2010
- [40] Gardner, Anthony D., Richter, Kai, Rosemann, Henning: Numerical Investigation of Air Jets for Dynamic Stall Control on the OA209 Airfoil, CEAS Aeronautical Journal, 1 (1-4), pp. 69-82, 2011

Task VIII – Rotor Wake Measurement Techniques (2003-2012)

- [41] Raffel, Markus, Favier, D., Berton, E., Rondot, E., Nsimba, M., Geißler, Wolfgang: Micro-PIV and ELDV wind tunnel investigations of the laminar separation bubble above a helicopter blade tip, Measurement, Science and Technology, 17 (7), pp. 1652-1658, 2006
- [42] Kindler, Kolja, Goldhahn, E., Leopold, F., Raffel, Markus: Recent developments in background oriented Schlieren methods for rotor blade tip vortex measurements, Experiments in Fluids, 43 (2-3), pp. 223-240, 2007
- [43] Raffel, Markus, Rondot, C., Favier, Didier, Kindler, Kolja: Microscale PIV Wind Tunnel Investigations. In: Adrian, R.J., Gharib, M., Rockwell, D. [Publ.]: Particle Image Velocimetry - A Practical Guide (2nd Edition), Experimental Fluid Mechanics, ISBN 978-3-540-72307-3, Springer: Berlin, Heidelberg, New York, pp. 358 - 363, 2007

- [44] Richard, Hugues, van der Wall, Berend G., Raffel, Markus: Stereo and Volume Approaches to Helicopter Aerodynamics. In: Adrian, R.J., Gharib, M., Rockwell, D. [Publ.]: Particle Image Velocimetry - A Practical Guide (2nd Edition), Experimental Fluid Mechanics, Springer: Berlin, Heidelberg, New York, pp. 317 - 327, 2007, ISBN 978-3-540-72307-3
- [45] Richard, Hugues, van der Wall, Berend, Raffel, Markus, Thimm, Michael: Application of PIV techniques for rotor blade tip vortex characterization. In: Tropea, Cameron, Jakirlic, Suad, Heinemann, Hans J., Henke, Rolf, Hönliger, Heinz [Pub.]: Notes on Numerical Fluid Mechanics and Multidisciplinary Design, NNFM, 96, Springer, pp. 446 - 454, International DGLR Symposium STAB, Darmstadt Germany, 2006, ISBN 3-54074-401-4
- [46] McAlister, Ken M., Heineck, James T., Raffel, Markus: Effects of Misalignment and Refraction on 3C PIV Measurements, Special Report AMR-CS-480, 2008
- [47] Kindler, Kolja, Mulleners, Karen, Richard, Hugues, Raffel, Markus: A Full-Scale Particle Image Velocimetry Investigation of "Young" Rotor Blade Tip Vortices, 65th Annual Forum of the AHS, Grapevine, TX, 2009
- [48] Mulleners, Karen, Henning, A., Mai, Holger, Raffel, Markus: Investigation of the Unsteady Flow Development over a Pitching Airfoil by Means of TR-PIV, 27th AIAA Applied Aerodynamics Conference, San Antonio, TX, 2009
- [49] Raffel, Markus, de Gregorio, Fabricio, Sheng, W., Gibertini, G., Seraudie, A., de Groot, Klaus, van der Wall, Berend G.: Generation of an Advanced Helicopter Experimental Aerodynamic Data-base - The Wind Tunnel Test of the EU-Project GOAHEAD –, ERF, Hamburg, Germany: 2009
- [50] Heineck, James T., Kushner, L.K., Schairer, E.T., Walker, L.A.: Retroreflective Background Oriented Schlieren (RBOS) as applied to Full-Scale UH-60 Blade Tip Vortices, American Helicopter Society Aeromechanics Specialists' Conference, San Francisco, CA, 2010
- [51] Heineck, James T., Schairer, E.T., Walker, L.A., Kushner, L.K.: Retroreflective Background Oriented Schlieren (RBOS), 14th International Symposium on Flow Visualization, Daeju, Korea, 2010
- [52] Raffel, Markus: PIV in Helicopter Aerodynamics, Invited Lecture, 19th Polish National Fluid Dynamics Conference, Poznan, Poland, 2010
- [53] Chernukha, P.A., Raffel, Markus, Kalugin, V.T.: Experimental and Numerical Modeling of Flow around Perforated Stabilizing Devices, 17th DGLR-Fach-Symposium der STAB, Berlin, Germany, 2010

- [54] Hernandez, R., Heine, Benjamin, Schneider, Oliver, Chernukha, P., Raffel, Markus: Visualization and Acquisition of Quantified Density Data of the Rotor Blade Tip Vortex, 17th DGLR-Fach-Symposium der STAB, Berlin, Germany, 2010
- [55] Richter, Kai, Rosemann, H.: Steady Aerodynamics of Miniature Trailing-Edge Devices in Transonic Flows, 29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, USA, 2011
- [56] Heine, Benjamin, Schanz D., Schröder, A., Dierksheide, U., Raffel, Markus: Investigation of the Wake of Low Aspect Ratio Cylinders by Tomographic PIV, 9th International Symposium on Particle Image Velocimetry, Kobe, Japan, 2011
- [57] Raffel, Markus, Hernandez-Rivera, R., Heine, Benjamin, Schröder, A., Mulleners, Karen: Density Tagging Velocimetry, Experiments in Fluids, 51 (2), pp. 573-578, 2011
- [58] Kindler, Kolja, Mulleners, Karen, Richard, Hugues, van der Wall, Berend G., Raffel, Markus: Aperiodicity in the near field of full-scale rotor blade tip vortices, Experiments in Fluids, 50 (6), pp. 1601-1610, 2011
- [59] de Gregorio, Fabricio, Pengel, Kurt, Kindler, Kolja: A Comprehensive PIV Measurement Campaign on Fully Equipped Helicopter Model, Experiments in Fluids, 53 (1), pp. 37-49, 2012

Task IX – Modeling and Simulation for Rotorcraft Systems (2003-2009)

- [60] Lusardi, Jeff A.: Control Equivalent Turbulence Input Model for the UH-60 Helicopter, US Army Special Report AMR-AF-06-01, 2006
- [61] Seher-Weiß, Susanne, von Grünhagen, Wolfgang: EC135 System Identification for Model Following Control and Turbulence Modeling, 1st CEAS European Air and Space Conference, Berlin, Germany, 2007
- [62] Hamers, Mario, Lantzsich, Robin, Wolfram, Jens: First Control System Evaluation of the Research Helicopter FHS, 33rd European Rotorcraft Forum, Kazan, Russia, 2007
- [63] Lusardi, Jeff A., von Grünhagen, Wolfgang: Parametric Turbulence Modeling for Rotorcraft Applications. Approach, Flight Tests and Verification, Rotorcraft Handling Quality Conference, University of Liverpool, UK, 2008

Task X – Handling Qualities for Active Controlled Rotorcraft (2003-2012)

- [64] Höfinger, Marc T., Blanken, Chris L., Strecker, G.: Evaluation of ADS 33-E Cargo Helicopter Requirements Using a CH-53G, 62nd Annual Forum of the AHS, Phoenix, AZ, 2006
- [65] Brenner, Hanno, Hamers, Mario: Preparatory Activities for CH-53 Flight Tests with a Slung Load, 62nd Annual Forum of the AHS, Phoenix, AZ, 2006
- [66] Höfinger, Marc T., Blanken, Chris L., Strecker, G.: Evaluation of Aeronautical Design Standard ADS 33-E Cargo Mission Requirements – Flight Tests with a CH-53G –, 32nd European Rotorcraft Forum, Maastricht, Netherlands, 2006
- [67] Blanken, Chris L., Hoh, Roger H., Mitchell, David G: Test Guide for ADS-33E-PRF, 63rd Annual Forum of the AHS, Virginia Beach, VA, 2007
- [68] Lantzsich, Robin, Wolfram, Jens, Hamers, Mario: Increasing Handling Qualities and Flight Control Performance using an Air Resonance Controller. 64th Annual Forum of the AHS, Montréal, Canada, 2008
- [69] Blanken, Chris L., Lusardi, Jeff A., Ivler, Christina M., Tischler, Mark B., Decker, William A., Malpica, Carlos A., Berger, Tom, Tucker, George E., Höfinger, Marc T.: An Investigation of Rotorcraft Stability-Phase Margin Requirements in Hover, 65th Annual Forum of the AHS, Grapevine, TX, 2009
- [70] von Grünhagen, Wolfgang, Müllhäuser, Mario, Abildgaard, Max, Lantzsich, Robin: Active Inceptors in FHS for Pilot Assistance Systems, 36th European Rotorcraft Forum, Paris, France, 2010
- [71] Lusardi, Jeff A., Blanken, Chris L., Ott, Carl L., Malpica, Carlos, von Grünhagen, Wolfgang: In Flight Evaluation of Active Inceptor Force-Feel Characteristics and Handling Qualities, 68th Annual Forum of the AHS, Ft. Worth, TX, 2012

Task XII – Active Individual Blade Control (2009-2012)

- [72] Coppotelli, G., Vetrano, F., Nitzsche, F., Feszty, D., Mander, A., Wierach, Peter, Riemenschneider, Johannes: Identification of the Dynamic Properties of Active Twist Rotor Model Blade Using Output-Only Data, IOMAC, Porto Novo, Ancona, Italy, 2009
- [73] Riemenschneider, Johannes, Opitz, Steffen, Wierach, Peter, Mercier des Rochettes, Hugues, Buchanek, L., Joly, D.: Structural design and testing of Active Twist Blades - A comparison, ERF, Hamburg, Germany, 2009

- [74] van der Wall, Berend G., Yin, Jianping: Cruise-Speed BVI Noise Computation by Comprehensive Code and Validation with HART I Data, 2nd International Forum on Rotorcraft Multi-disciplinary Technology, Seoul, Korea, 2009
- [75] Lim, Joon W., Dimanlig, A.C.B.: An Investigation of the Fuselage Effect for HART II Using a CFD/CSD Coupled Analysis, 2nd International Forum on Rotorcraft Multidisciplinary Technology, Seoul, Korea, 2009
- [76] Lim, Joon W., van der Wall, Berend G.: An Assessment of 3-C PIV Analysis Methodology for HART II Measured Data, NASA TM-2010-216024, AFDD TR RDMR-AF-10-03, 2010
- [77] Opitz, Steffen, Riemenschneider, Johannes, Monner, Hans P.: Modal Investigation of an Active Twist Helicopter Rotor Blade, 20th International Conference on Adaptive Structures and Technologies (ICAST), Hong Kong, China, 2009
- [78] Opitz, Steffen, Riemenschneider, Johannes, Hoffmann, Frauke, Schneider, Oliver: Measurement of the Dynamic Tip Twist Angle of an Active Twist Model Scale Rotor Blade, 36th European Rotorcraft Forum, Paris, France, 2010
- [79] Hoffmann, Frauke, Opitz, Steffen, Riemenschneider, Johannes: Evaluation of Two Different Active Twist Simulation Models Using Experimental Data, On-era/DLR Aerospace Symposium (ODAS), Berlin, Germany, Oct. 6-8, 2009
- [80] Lim, Joon W., Dimanlig, A.C.B.: The Effect of Fuselage and Rotor Hub on Blade-Vortex Interaction Airloads and Rotor Wakes, 36th European Rotorcraft Forum, Paris, France, 2010
- [81] van der Wall, Berend G.: Evolution of Prescribed Wake Modeling for Helicopter Rotors with Special Emphasis on BVI Noise, 4th AHS International Meeting on Advanced Rotorcraft Technology and Safety Operations (Heli Japan), Omiya Sonic City, Saitama, Japan, 2010
- [82] Lim, Joon W., van der Wall, Berend G.: An Assessment of 3-C PIV Analysis Methodology for HART II Measured Data. NASA/TM-2010-216024, TR-RDMR-AF-10-03, 2010
- [83] Monner, Hans P., Riemenschneider, Johannes, Opitz, Steffen, Schulz, M.: Development of Active Twist Rotors at the German Aerospace Center (DLR), 19th AIAA/ASME/AHS Adaptive Structures Conference, Denver, CO, 2011
- [84] Opitz, Steffen, Riemenschneider, Johannes, Schulz, M.: Prerequisites for the Closed Loop Control of an Active Twist Rotor Blade, 67th Annual Forum of the AHS, Virginia Beach, VA, 2011
- [85] Riemenschneider, Johannes, Opitz, Steffen: Measurement of Twist Deflection in Active Twist Rotors, AST Journal, 15 (3), pp. 216-223, 2011

- [86] van der Wall, Berend G.: Helicopter Rotor BVI Airloads Computation Using Advanced Prescribed Wake Modeling, 29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, USA, June 2011
- [87] van der Wall, Berend G.: Prescribed wake modifications to account for harmonic rotor loading and validation with HART data, 67th Annual Forum of the AHS, Virginia Beach, VA, 2011
- [88] van der Wall, Berend G.: A Comprehensive Rotary-Wing Data Base for Code Validation: The HART II International Workshop, The Aeronautical Journal, 115 (1164), pp. 91-102, 2011, Royal Aeronautical Society, ISSN 0001-9240
- [89] Lim, Joon W., Wissink, A., Jayaraman, Buvana, Dimanlig, A., Wake, B., Makinen, S.: Helios Adaptive Mesh Refinement for HART II Rotor Wake Simulations, 68th Annual Forum of the AHS, Ft. Worth, TX, 2012
- [90] van der Wall, Berend G., Lim, Joon W., Smith, Marilyn J., Jung, Sung N., Bailly, Joëlle, Baeder, James D., Boyd, D. Douglas: An Assessment of Comprehensive Code Prediction State-of-the-Art Using the HART II International Workshop Data, 68th Annual Forum of the AHS, Ft. Worth, TX, 2012
- [91] Smith, Marilyn J., Lim, Joon W., van der Wall, Berend G., Baeder, James D., Biedron, Robert T., Boyd, D. Douglas, Jayaraman, Buvana, Jung, Sung N., Min, Byung-Young: An Assessment of CFD/CSD Prediction State-of-the-Art Using the HART II International Workshop Data, 68th Annual Forum of the AHS, Ft. Worth, TX, 2012
- [92] van der Wall, Berend G.: Extensions of Prescribed Wake Modelling for Helicopter Rotor BVI Noise Investigations, CEAS Aeronautical Journal 3 (1), pp. 93-115, 2012
- [93] Bauknecht, Andre, Sa, J.H., van der Wall, Berend G.: Expansion of the prescribed wake code of the rotor simulation program S4 with a CFD-based model of the fuselage-induced velocity, DLR-IB 111-2012/62, 2012

Task XIII – Obstacle Field Navigation for Unmanned Rotorcraft (2010-2012)

- [94] Mettler, B., Kong, Z., Goerzen, Chad, Whalley, Matthew: Benchmarking of Obstacle Field Navigation Algorithms for Autonomous Helicopters, 66th Annual Forum of the AHS, Phoenix, AZ, May 11-13, 2010
- [95] Whalley, Matthew, Dittrich, Jörg, Adolf, Florian, Goerzen, Chad: Obstacle Field Navigation Benchmarking and Metrics, Comparison of Phase 1 Results, 16 October 2012

